1 **SEGMENTED COMPLEX DIFFRACTION GRATINGS**

2

3 **Related Applications:**

4 The present application is a continuation in part of Application serial number 09/100,592

5 which was filed June 19, 1998 and which is now pending, a continuation in part of

6 Provisional Application 60/070,684, which was filed January 1, 1998, and a continuation

7 in part of Application serial number 08/897,814 filed July 21, 1997 and which is now

8 pending and which is a continuation of Application serial number 08/403,376 which was

9 filed March 13, 1995 and which is now abandoned.

10

11 **Field of the Invention:**

12 The present invention relates to optical communication systems and more particularly to

13 the use of complex gratings in communication systems.

14

15 **Background of the invention:**

16 Many present optical communication systems utilize wavelength division multiplexing

17 (WDM) to increase the capacity of optical fibers. Co-pending patent applications SN

18 08/403,376 and 60/070,684 which are referenced above describe a technology for

19 increasing the capacity of optical systems by utilizing a different type of multiplexing

20 which can be termed optical code division multiple access (hereinafter OCDMA).

21 OCDMA systems encode different communication channels with different temporal

22 codes as contrasted to the coding in WDM systems wherein different channels use

23 different wavelengths of light.

24

1 Co-pending patent applications SN 08/403,376 and 60/070,684 describe diffraction

2 gratings which consist of multiple sinusoidal subgratings, each subgrating having a

3 specific amplitude and spatial phase. Such gratings can deflect optical pulses from a

4 specific input direction to a specific output direction while simultaneously multiplying the

5 Fourier spectrum of the input pulse by a predetermined filtering function. The output

6 signals are a cross-correlation between the input waveform and the grating encoded

7 temporal waveform. The gratings described in the referenced co-pending applications

8 have a complex profile. They can accept input beams and generate spectrally filtered

9 output beams propagating in one or more output directions. The filtering function of the

10 device is programmed by choice of grating profile. By suitable programming, multiple

11 transfer functions may be realized, each having its own specific input and output

12 direction.

13

14 **Summary of the present invention:**

15 The present invention provides a structure (i.e. a segmented grating) which applies a

16 designated complex-valued spectral filtering function to the input optical field and emits

17 a filtered version of the input field in an output direction and a method for making such a

18 structure. Grating devices, comprised of one or more segmented gratings after the

19 present invention can be used, for example, in OCDMA data links to temporally code

20 optical signals with specific codes such that multiple coded channels can simultaneously

21 be transmitted through the same link and then be decoded into separate channels at the

22 output of the system. The segmented gratings of the present invention can also be

23 utilized in any application area wherein the ability to effect programmable spectral

24 filtering is utilized. The segmented gratings fabricated in accordance with the present

25 invention consist of a series of spatially distinct subgratings arrayed end to end. Each

1   subgrating possesses a periodic array of diffraction structures (lines or more general

2   elements). The overall transfer function of the segmented grating is determined by

3   controlling (a) the spatial periodicity or frequency of each subgrating, (b) the amplitude

4   of each subgrating,(c) the spacing between the last diffraction structure (or line) on each

5   subgrating and the first diffraction structure (or line) of the successive subgrating, and

6   (d) the optical path length and transparency through each subgrating, or each

7   subgrating plus additional material layers utilized to control optical path length and

8   transparency.

9

10   **Brief Description of the Figures:**

11   Figure 1A is an overall diagram of a multiplexing/demultiplexing system utilizing the

12   present invention.

13

14   Figure 1B shows in more detail one of the optical paths shown in Figure 1A.

15

16   Figure 2A shows a top view of a segmented grating fabricated in accordance with the

17   present invention.

18

19   Figure 2B shows a side view of a segmented grating fabricated in accordance with the

20   present invention.

21

22   Figure 3A is a schematic diagram showing the input angle and the output angle at which

23   light is passed through the segmented grating.

24

1   Figure 3B is a schematic diagram showing the angle between the plane containing the

2   input and output beams and the x axis, as measured in the x-y plane.

3

4   Figure 3C shows a temporally coded optical pulse composed of 4 time slices that is

5   incident on a segmented grating of 4 contiguous equal width subgratings.

6

7   Figure 4 shows a first technique for fabricating segmented gratings according to the

8   present invention.

9

10   Figure 5 shows a second technique for fabricating segmented gratings according to the

11   present invention.

12

13   Figure 6 shows a third technique for fabricating segmented gratings according to the

14   present invention.

15

16   Figure 7 shows a side view of two subgratings of a segmented grating with different

17   optical thickness.

18

19   Figure 8 shows a side view of two subgratings of a segmented grating which have a saw

20   tooth blaze.

21

22   Figure 9 shows a four channel OCDMA system.

23

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Detailed Description of a Preferred Embodiment:

Figure 1A is an overall diagram of an OCDMA communication system which utilizes the segmented diffraction grating of the present invention to perform optical multiplexing and demultiplexing. Short-pulse laser 10 generates a coherent beam of light 12. Beam splitter 13 divides the light into two beams 15 and 16. Beams 15 and 16 are each individually modulated by modulators 15a and 16a respectively, thereby generating modulated beams 15b and 16b. The modulation of each of the beams is done in response to an external data stream not explicitly shown in Figure 1. Beams 15b and 16b consist, either by virtue of the operative character of the laser source 10, the action of the modulators 15a and 16a, or a combination of the two, of a stream of bits whose temporal character matches the designed input pulses of grating 19.

Each of the beams 15b and 16b is directed at grating 19 so that it is incident on the grating 19 at an angle that differs for each beam. Grating 19 is a grating device comprised of two superimposed segmented gratings operative on beams 15b and 16b to produce separate output time codes in optical transport 11 for each of the input beams. (The coding technique and the details of grating 19 are described below). The combined coded beam is transported to a second grating 19a via an optical transport device 11 which may for example be an optical fiber. Grating 19a is a grating device also composed of two superimposed segmented gratings operative on the time codes in beam 11 to produce output beams 15c and 16c, respectively. Beams 15c and 16c are modulated identically to the corresponding beam 15a or 16a, respectively. (The decoding technique and the details of grating 19a are described below). The content of beams 15c and 16c is detected by detectors 15d and 16d and it is thus turned back into

1   electrical signals which correspond to the signals that activated modulators 15a and

2   16a.

3

4   It is noted that while the embodiment shown herein combines two beams into one coded

5   beam, three, four, or more beams could similarly be multiplexed into one beam using

6   OCDMA coding. The combined coded beam could be transmitted over a transmission

7   system and then the beams could be demultiplexed into the original signals.

8   Figure 1B shows the optical lenses and spatial filters associated with passing one of the

9   beams through gratings 19 and 19a. As shown in Figure 1B the light beam 16b is

10   passed through a collimating lens 6a so that the light beam illuminates the entire

11   operative width of the two dimensional segmented grating 19sg16 contained within

12   grating device 19. A second lens 6B focuses the light passing through grating device 19

13   into optical transport 11.   Spatial filtering provided by means of a dedicated element 8a

14   or consequent to entry into the optical transport selects the operative angular output

15   channel of the segmented grating 19sg16. At the end of optical transport 11 a second

16   collimating lens 7a illuminates segmented grating 19asg16 over (constituent to grating

17   device 19a) over its operative width and the light passing through grating 19a is focused

18   by collimating lens 7b. A spatial filter 8b following lens 7b selects the operative output

19   angular channel of the segmented grating 19asg16 of grating 19a. Figure 1B only

20   shows the elements associated with one data path. The system includes mechanism

21   for collimating each of the beams 15b and 16b, and providing for said beams to

22   illuminate corresponding segmented gratings 19sg15 and 19sg16 within grating 19 at a

23   different angle. A separate lens 6a for each input beam provides an exemplary

24   mechanism. Alternatively, a single lens and control over the launch conditions of the

25   input beams toward the single lens provides equivalent function. Exemplary spatial

1   control comprises a spatial filter in the front focal plane of said single lens with apertures

2   sufficiently small to provide diffractive grating filling. At the output of grating 19a, there

3   is a mechanism for providing a spatial Fourier decomposition of the angular output of

4   the segmented gratings comprising grating 19a and appropriate spatial filtering

5   mechanisms for selecting the multiple operative angular output channels. A single lens

6   provides an exemplary mechanism for providing spatial Fourier decomposition.

7   Apertures placed in the focal plane of said single lens then provides means of selecting

8   operative angular channels. Other means for selecting operative angular channels are

9   are known in the art

10

11   Gratings 19 and 19a through their constituent segmented gratings are designed to

12   accept light from one or more directions and to redirect the light into one or more output

13   directions in a manner that is dependent on the temporal waveform of the input light.

14   Considering a specific input direction and one of the output directions associated with

15   this specific input direction, the grating's functions can be summarized as follows: A

16   portion of each spectral component of the input light field is mapped into the output

17   direction with a controlled amplitude and phase. The grating applies a designated

18   complex valued spectral filtering to the input optical field and emits the filtered version of

19   the input field in the output direction. The spectral resolution of the filtering function is

20   determined by the physical size of the enabling segmented grating constituent to the

21   operative grating device along with the input and output angles of the light beam relative

22   to the grating. The spectral mapping between each input direction and each output

23   direction may be programmed essentially independently through use of dedicated

24   segmented gratings for each mapping. This is explained in the previously referenced

25   co-pending applications, the description of which is incorporated herein by reference.

1   In the present invention, each independently controllable spectral transfer function is

2   controlled by a segmented grating.

3

4   Figure 2A shows one segmented grating fabricated in accordance with the present

5   invention. Grating 19 and 19a contain two such structures superimposed on each other

6   as to form one combined grating. The combined grating thus incorporates the structure

7   of the two individual segmented gratings. We focus now on the design of a single

8   segmented grating. Grating devices incorporating multiple segmented gratings are

9   designed through repetitive application of single segmented grating procedures. The

10   segmented grating has N spatially distinct subgratings or sections 1 to N. In the

11   embodiment shown N is equal to eight. An exemplary cross section of the segmented

12   grating is shown in Figure 2B. Figure 2B is only presented for illustrative purposes to

13   show that the line structure on each of the subgratings comprising the segmented

14   grating has its own amplitude and phase.

15

16   In order to mathematically define the structure of the subgratings contained within one

17   segmented grating, it is first necessary to define a set of coordinates and angles

18   descriptive of the segmented grating and associated optical input and output directions.

19   For convenience, we chose the origin of the reference coordinate axes to lie in the

20   center of the segmented grating. The segmented grating surface is taken to coincide

21   with the x-y plane. We define two lines each of which passes through the coordinate

22   center with the first line parallel to the optical input direction and the second parallel to

23   the optical output direction. We refer to these two lines as the input and output lines,

24   respectively. The input and output lines define a plane, referred to herein as the

25   input/output plane. The mathematics presented herein has the x-axis located in the

1   input/output plane. Other embodiments of the invention could have structures wherein

2   the z-axis is noncoplanar with the input and output lines. Figures 3A and 3B show a

3   schematic diagram of a segmented grating structure showing input angle (θ_{in}) and output

4   angle (θ_{out}) in the input/output plane. The angular separation between the input (output)

5   direction and the z axis is θ_{in} (θ_{out}), where the angles are positive as shown in Figure 3A.

6   Figure 3B shows the angle θ_a between input/output plane and the x axis as measured in

7   the x-y plane. Thus, Figures 3A and 3B show the geometrical arrangement of a

8   segmented grating relative to a particular input and output optical field. For the particular

9   segmented grating under consideration, we define the groove-normal line as the line

10   perpendicular to the grooves lying in the plane of the segmented grating surface and

11   passing through the origin. As described above, the groove-normal line is contained

12   within the input/output plane. Other embodiments of the invention could have a groove-

13   normal line at other locations relative to the input/output plane.

14

15   When the input/output plane contains the z axis, the diffractive structures (grooves) that

16   redirect and spectrally filter the input optical beam into the output direction lie

17   perpendicular to the input/output plane and lie within or on the surface of the segmented

18   grating. We reiterate that multiple segmented gratings having the same or different

19   values of θ_a can be colocated on the same substrate with any degree of overlap.

20   Grating devices may require a single segmented grating structure, multiple spatially

21   superimposed segmented grating structures, or a combination of spatially superimposed

22   and spatially separated segmented grating structures fabricated onto a single substrate.

23   Grating 19 in Figure 1A is comprised of two segmented grating structures.

24

1   Grating 19 utilizes transmissive segmented gratings, but all particulars discussed herein

2   can be transferred as known in the art to a reflective grating geometry. Each input

3   optical beam illuminates the active width of each segmented grating structure with which

4   it is intended to interact. It is noted that grating 19 and the segmented gratings that it

5   supports are essentially planar and arranged parallel to the x-y coordinate plane. As in

6   the case of simple monospaced diffraction gratings, segmented gratings may be

7   implemented with nonplanar surface geometry. For example a segmented grating could

8   be supported by a nonplanar (e. g. concave) substrate. The use of non-planar surface

9   geometry allows for the control over the spatial wavefront of input optical beams in

10 addition to the spectral content control that is afforded by grating segmentation.

11

12 A single segmented grating structure is fabricated in the form of a series of N spatially

13 distinct subgratings arrayed side to side whose collective span defines the operative

14 width of the segmented grating. Each subgrating possesses a periodic array of

15 diffractive structures (grooves) arranged in a plane perpendicular to the input/output

16 plane. The spacing between diffractive structures within the N successive spatial

17 subgratings is typically but not necessarily the same. The N subgratings are written or

18 otherwise created on the grating such that each occupies a specific subsection of the

19 overall grating surface and subgratings appear successively as one passes along the

20 groove-normal line. All subgrating constituents of a particular segmented grating

21 typically but not necessarily have the same span perpendicular to the groove-normal

22 line, i.e. height. The spatial interval between the last diffractive structure (groove) of

23 each subgrating and the first diffractive structure (groove) of the successive subgrating

24 is controlled as will be described.

25

1   Control over groove positioning provides control over relative spatial phase of adjacent

2   subgratings. Also controlled is the amplitude of the diffractive structures within a given

3   subgrating. The manner in which subgrating spacing and amplitude is controlled

4   determines the spectral transfer function of the grating. The optical thickness of the

5   various subgratings comprising a segmented grating structure can be controlled by

6   variation of substrate thickness, addition of phase masks, or other means known in the

7   art to provide additional control over the spectral transfer function of the grating.

8   Variation of optical thickness under a spatial subgrating or the separation between

9   subgratings both act to control the relative phase of light transferred from the input to

10   the output directions. Active devices can be added between the subgratings to

11   dynamically change subgrating-subgrating separation to allow for the dynamical

12   reprogramming of the spectral filtering function. Active devices to control the optical

13   thickness of subgratings inclusive of overlays can be added to provide an alternative

14   means of dynamical reprogramming of the spectral filtering function.

15

16   The representative segmented grating shown in Figure 2 has eight spatial subgratings.

17   The spatial subgratings have essentially equal extent along the groove normal line;

18   however, spatial subgratings of dissimilar extent can be employed. The representative

19   segmented grating is a transmissive phase grating, but it could be a reflective,

20   amplitude, or other generalized physical grating type.

21

22   We represent the transmissive optical phase shift versus position of one

23   constituent subgrating, labeled by the subscript i, of a segmented grating device by the

24   following mathematical expression

1     $h_i(x') = A_i f_i(2\pi(x' - x_i)/\Lambda_i) + \varphi_i$ {for $x_i^a \leq x' \leq x_i^b$}   (1)

2   where x' represents the spatial position coordinate along the groove-normal line, x_i is the

3   spatial position shift of the ith subgrating groove pattern, the function f_i represents a

4   particular groove profile and is periodic in its argument on the scale of 2π and modulates

5   between the values of 0 and 1, φ_i is an optical phase shift introduced by a variation in

6   substrate thickness or superimposed phase mask, A_i is a real-valued amplitude factor,

7   x_i^a and x_i^b are the edge positions of subgrating i, and Λ_i is the spatial period of the ith

8   subgrating. Outside the prescribed spatial interval, $h_i(x')=0$. The subscript i ranges from 1

9   to N and denotes individual spatial subgratings. By specifying the parameters A_i, φ_i,

10   x_i, and Λ_i for the subgratings employed, a wide range of spectral filtering functions can

11   be encoded.

12

13   The parameters A_i, φ_i, x_i, and Λ_i necessary to produce specific spectral transfer

14   functions can be chosen in a variety of ways. Assume that a grating is to be constructed

15   that provides a particular spectral transfer function $T(v)$ (where v is the optical

16   frequency) as approximated by N transmission coefficients each of which corresponds

17   to one of N contiguous frequency channels collectively spanning the full non-zero width

18   of $T(v)$. To accomplish this, the segmented grating will require approximately N

19   subgratings. We assume that $T(v)$ is nonzero over a specific spectral region of width δv

20   centered about the frequency v_0. To provide filtering with the specified resolution, the

21   subgratings will require a spatial width given approximately by $c/[\delta v(\sin\theta_{in}+\sin\theta_{out})]$ where

22   c is the speed of light. The total width of the grating will thus be approximately given by

23   $Nc/[\delta v(\sin\theta_{in}+\sin\theta_{out})]$ assuming that the subgratings are laid down contiguously.

1

2   For example, if $\delta v = 100$ GHz, $\theta_{in} = 0°$, $\theta_{out} = 45°$, and $N=8$ the complete spatial width of a

3   segmented grating capable of representing $T(v)$ will be approximately 3.4 cm.

4

5   The parameters $(A_i, \varphi_i, x_i, \text{ and } \Lambda_i)$ for all of the N subgratings comprising the

6   segmented grating determine its spectral transfer function. Given the subgrating

7   parameters, the spectral transfer function of the segmented grating can be determined.

8   Conversely, given a specific spectral transfer function the subgrating parameters which

9   must be employed to create a segmented grating with that transfer function can be

10   determined. It should be understood that while the mathematics presented herein

11   contain certain constraining assumptions in order to facilitate an explanation of the

12   preferred embodiment of the invention, the equations could be generalized without

13   departing from the invention.

14

15   We first give an expression for the spectral transfer function exhibited by a segmented

16   grating in terms of subgrating parameters. Under the assumptions that 1) $A_i \ll 1$ or

17    $A_i = A = $constant, 2) plus or minus first order ($m = \pm 1$) grating output is employed, and 3)

18   the N subgratings have equal spatial width ($d = x_i^b - x_i^a = $constant), equal spatial period

19   ($\Lambda_i = \Lambda = $constant), and are laid down contiguously, the spectral transfer function of the

20   segmented grating may be written as a sum over subgrating parameters as follows:

21
$$T(v) = F(v) \sum_{i=1}^{N} a_i \exp(j\Phi_i) \qquad \text{(2a)}$$

22   where:

23
$$a_i = A_i \exp(j(\varphi_i - 2\pi x_i m / \Lambda)), \qquad \text{(2b)}$$

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1 $$\Phi_i = \pi(x_i^a + x_i^b)(\beta v - m/\Lambda)),\qquad(2c)$$

2 and

3 $$\beta = (\sin\theta_{in} + \sin\theta_{out})/c.\qquad(2d)$$

4

5 Here, F(v) is the spatial Fourier transform of a subgrating given by

6 $$F(v) = \frac{jC}{N}\operatorname{sinc}(\pi d(v\beta - m/\Lambda)),\qquad(2e)$$

7 where j is $\sqrt{-1}$, and C is a constant dependent on the groove profile and contains a

8 phase factor dependent on the choice of x'-origin. The function sinc(x) is defined as

9 equal to sin(x)/x. In writing Eq. (2), it is assumed that the output signal is derived from

10 the plus (m=1) or minus one (m=-1) diffractive order of the subgratings. Analogous

11 expressions for higher and negative orders follow as per known in the art.

12 If one wishes to design a segmented grating having a specific transfer function, it

13 is necessary to determine appropriate parameters for each subgrating. To do this one

14 first solves Eq. (2a) for a_i and obtains

15

16 $$a_i = \beta d \int_{m/(\beta\Lambda)-1/(2\beta d)}^{m/(\beta\Lambda)+1/(2\beta d)} \frac{T(v)}{F(v)}\exp(-j\pi(v\beta - m/\Lambda)(x_i^a + x_i^b))dv\qquad(3)$$

17

18 From Eq. (2b) one finds that A_i is equal to the amplitude of a_i. The quantities x_i and φ_i

19 both determine the phase of a_i as seen in the equations above. An appropriate

20 combination of x_i and φ_i consistent with Eq. (2b) and Eq. (3) can be chosen at the

21 convenience of the grating designer. The parameter Λ is chosen so the light of carrier

1   frequency v_o is maximally diffracted from θ_{in} to θ_{out} using the well-known grating equation

2   $sin(\theta_{in}) + sin(\theta_{out}) = m\lambda_o / \Lambda$ where $\lambda_o = c/v_o$ is the center wavelength of the desired transfer

3   function. The angles θ_{in} and θ_{out} are designer inputs as is T(v). Mathematically

4   speaking, Λ is chosen as the solution of the mathematical equation $\beta v_o \Lambda = m$.

5

6   Alternatively, a more general solution for obtaining the subgrating parameters is to

7   calculate the continuous grating profile that will generate the desired continuous transfer

8   function. If the transmissive phase of a grating as a function of x' is given by

9
$$h(x') = -j \ln\left[\sqrt{2\pi}\beta D \int_{-\infty}^{+\infty} T(v)\exp(-j2\pi\beta vx')dv \right], \qquad (4)$$

10   the spectral transfer function of the grating in direction θ_{out} will be T(v), where D is the

11   width of the grating. Again θ_{in}, θ_{out}, and T(v) are designer inputs. It is necessary to

12   convert the continuous transmissive phase profile given by Eq. (4) to a segmented

13   phase profile consistent with subgrating fabrication. Parameters descriptive of constant

14   phase segments which can be directly mapped onto the parameters defining constituent

15   subgratings can be determined as follows: The continuous surface phase profile, $h(x')$,

16   will generally consist of a carrier spatial modulation with a slowly varying amplitude and

17   phase shift. A representative average of the spatial phase shift over the physical extent

18   of subgrating i is determined and the values of φ_i and x_i are adjusted in a convenient

19   combination to match the determined spatial phase shift determined from Eq. (4).

20   Similarly, a representative value of the grating amplitude from Eq. (4) within the physical

21   extent of subgrating i is determined and A_i is set equal to this grating amplitude. The

22   spatial period Λ_i is set equal to the carrier modulation period of $h(x')$ as given by Eq. (4).

23   A variation to the approach just given is to determine a spatial carrier, amplitude, and

1   phase within the extent of each subgrating separately. This procedure allows for the

2   variation of Λ_i from subgrating to subgrating.

3

4   For a segmented grating to perform the function of optical cross-correlation between

5   optical input waveforms and a reference optical waveform, the grating's spectral transfer

6   function should be the complex conjugate of the spectrum of the reference optical

7   waveform. The function of optical cross correlation here means that the electric field

8   emitted by the grating in the operative output direction represents the temporal cross

9   correlation between a) an input optical waveform incident on the grating along the

10   operative input direction and b) the specific reference optical waveform whose

11   conjugated spectrum coincides with the grating's spectral transfer function.

12

13   Consider a reference optical waveform whose time profile is represented as a sequence

14   of N contiguous time slices within which the amplitude and phase of the optical field is

15   constant. In time slice i ($i=1,..,M$), the electric field has constant amplitude B_i and phase

16   ϕ_i. The reference waveform is thus determined by the set of complex numbers

17   $[B_1\exp(j\phi_1), B_2\exp(j\phi_2),...,B_M\exp(j\phi_M)]$ along with the optical carrier frequency in each time

18   slice and the overall temporal duration of the waveform Figure 3C schematically

19   illustrates an input optical waveform of the form $[C_1\exp(j\phi'_1), C_2\exp(j\phi'_2),...,C_4\exp(j\phi'_4)]$

20   incident on a segmented grating.

21

22   When an optical waveform is incident on the grating, the grating will spectrally filter the

23   incident waveform as described by the grating spectral transfer function for the particular

24   θ_{in} and θ_{out} employed. If the grating is to perform the function of cross-correlation

25   against the reference optical waveform, the subgratings should have parameters that

1   are the "time-reversed" complex conjugate of the reference optical waveform, e.g. [a_1,

2   a_2,..., a_8] = [$B_8 exp(-j\phi_8)$, $B_7 exp(-j\phi_7)$,...,$B_1 exp(-j\phi_1)$)] where the subgrating parameters are

3   related to a_i by equation (2b) given the assumptions in deriving Eqs. (2a-3) are met.

4   The operation of cross-correlation may be used to multiplex and demultiplex optical

5   signals.

6

7   It is noted that the groove profile affects primarily the diffraction efficiency of the grating.

8   This affects the magnitude of the spectral transfer function or the constant C in Eq. (2e).

9

10   The following specifies the gratings employed in an exemplary two-channel

11   multiplex/demultiplex system as in Figure 1a. Grating devices 19 and 19a used are

12   each composed of two superimposed segmented gratings. Grating 19 accepts uncoded

13   data streams and launches time-coded data into a common channel. Grating 19a

14   accepts time-coded data and launches distinct time codes into distinct output directions

15   while simultaneously stripping off time-coding. Grating 19a functions through the

16   process of cross-correlation.

17

18   In the present embodiment, gratings 19 and 19a consist of two superimposed

19   segmented gratings. The net transmissive optical phase shift versus position of the

20   gratings is consequently the sum of the transmissive optical phase shift functions for the

21   two constituent segmented gratings.

22

23   In the multiplexer/demultiplexer embodiment presently considered we use a lamellar

24   (square-wave) groove profile with a fifty percent duty cycle. We assume uniform

25   subgrating amplitudes of $A_i = \pi/2$ for the first and second segmented gratings, the

1   diffraction efficiency of grating 19 and grating 19a is approximately 20% in the operative

2   output directions. If a transmission grating is to be etched into a substrate with optical

3   index n_o=1.50, the etch depth that corresponds to $A_i=\pi/2$ phase modulation is given by

4   0.77μm for a carrier wavelength of 1.54μm. The input-output plane contains the z-axis

5   in this embodiment. The gratings 19 and 19a have eight subgratings, each subgrating

6   has a width of 1mm, thus the total grating width is 8mm. The segmented gratings

7   comprising grating 19 and 19a have θ_a=0° and are designed for optical data streams

8   having the carrier frequency 195 THz (a carrier wavelength λ=1.54μm).

9

10   The optical data channels controlled by a first segmented grating constituent of grating

11   19 are specified to have the input and output angles θ_{in}=17.94° and θ_{out}=0°. The grating

12   spacing is Λ=5 μm for all subgratings of the first segmented grating. The first

13   segmented grating is designed to accept temporally short input pulses of optimal

14   duration $\Delta\tau_p$=1 ps along θ_{in}=17.94° and generate temporally coded pulses along the

15   multiplexed output direction θ_{out}=0°. To produce output pulses of approximate duration

16   τ_p=8 ps with the following temporal code

17   [1, 1, 1, exp(j2π/3), exp(j4π/3),1, exp(j4π/3), exp(j4π/3)]

18   the corresponding subgrating x_i and φ_i parameters for the first segmented grating are

19          $[x_1, x_2,..., x_8]$=[0.0μm, 0.0μm, 0.0μm, -1.67μm, 1.67μm, 0.0μm, 1.67μm, 1.67μm]

20   and

21          $[\varphi_1, \varphi_2,..., \varphi_8]$=[0,0,0,0,0,0,0,0].

22   The second segmented grating consists of a set of eight subgratings with the following

23   common specifications: Λ=3 μm, θ_{in}=30.89°, θ_a=0°, and θ_{out}=0°. The second segmented

24   grating, like the first, accepts temporally brief data bits of optimal duration $\Delta\tau_p$≈1.71 ps

1   moving along its input direction and generates temporally coded bits of approximate

2   duration τ_p=13.7 ps into its output direction. Segmented gratings one and two have a

3   common output direction. If the coded output bits from segmented grating two are to

4   have the following form

5   [1, exp(j2π/3), exp(j4π/3), 1, exp(j2π/3), exp(j4π/3), 1, exp(j2π/3)],

6   the corresponding subgrating parameters of the second segmented grating are

7         $[x_1, x_2,..., x_8]$=[0.0μm, -1.0 μm, 1.0 μm, 0.0μm, -1.0 μm, 1.0 μm, 0.0μm, -1.0 μm]

8   and

9         $[\varphi_1, \varphi_2,..., \varphi_8]$=[0,0,0,0,0,0,0,0].

10   The filtering bandwidth of the second segmented grating is $\delta v \cong 1/\Delta\tau_p$ or 0.6 THz.

11

12   The multiplexed beams copropagating in optical transport 11 may be demultiplexed at

13   grating 19a. The demultiplexing grating 19a in Figure 1A and 1B is identical in design to

14   grating 19. For an input angle into grating 19a of θ_{in}=0° the demultiplexed output beams

15   are collected in angles θ_{out} =–17.94° and θ_{out} =–30.89° for the first and second reference

16   optical waveforms respectively.

17

18   Given the above grating specifications the laser source 10 as shown in figure 1A must

19   have a maximum temporal pulse width (FWHM) of 1 ps (given by the minimum $\Delta\tau_p$ of the

20   two segmented gratings).

21

22

23   <u>Manufacturing segmented gratings</u>: Using lithography (optical or electron beam)

24   surface profiles can be written onto a substrate point by point. Thus segmented gratings

25   with spatial phase shifts between the subgratings can be written directly onto a

1   transmitting or reflecting surface. Control of subgrating amplitude is also possible using

2   this technique.

3

4   It is also possible to use a variety of holographic techniques to successively or

5   simultaneously record subgratings with controlled surface profile properties.

6

7   Figure 4 illustrates how the segmented grating can be manufactured by spatial

8   repositioning of the grating substrate to produce subgratings with controlled spatial

9   phase. The angle between the two beams or the wavelength of the two beams used in

10   standard holographic recording can be used to control the grating spacing Λ_i. Spatial

11   phase shifts may be introduced between exposures by translating the grating substrate.

12   Thus, the N subgratings can be recorded, as shown in Figure 4, by spatially translating

13   an aperture mask of width d=D/N (where D is the total grating length) by its width N

14   times and exposing the recording material at each mask position. Between exposures,

15   the grating substrate is shifted along the groove-normal line. The substrate shifts a

16   distance x_i relative to a fixed reference prior to exposure of subgrating i. Control of

17   writing beam intensity between subgrating exposures allows for subgrating amplitude A_i

18   control.

19

20   A similar method of producing segmented gratings comprised of subgratings with spatial

21   phase shifts uses single exposure holography with a phase-code mask having the

22   appropriate subgrating phase shifts encoded in its optical thickness. The mask is placed

23   in one of the two interfering beams in close proximity to the substrate. If these beams

24   are incident from opposite sides of the substrate, this phase-mask can be contacted

25   directly onto the grating substrate.

Figure 5 shows a holographic method for fabricating gratings with N subgratings with controlled spatial phase shifts. This technique controls the phase-difference, ϕ_i, between the two optical writing beams as shown in Figure 5. Control of writing beam intensity allows for control of subgrating amplitude as well. The optical phase-difference determines the position of the interference pattern on the sample where the beams overlap, and their intensity controls the modulation amplitude of the interference pattern. The subgratings are recorded by illuminating the whole sample region with the interference pattern, but using an aperture of width d so that only the region behind the aperture is exposed and recorded. By spatially shifting the aperture across the sample in N steps it is possible to write a series of N subgratings, with each grating having a phase determined by the phase-difference ϕ_i used during exposure of the ith subgrating.

Figure 6 illustrates an approach to producing subgratings termed the "master phase mask" approach. In this approach a single writing beam is used in conjunction with a master phase mask diffraction grating. A single beam incident on a master grating will be diffracted to yield one or more extra output beams. The incident and diffracted beams will interfere producing an interference pattern that can be used to record a near duplicate of the master grating as known in the art. This property of diffraction gratings makes it possible to use a master grating to generate the interference pattern needed for the grating. The phase in each subgrating is imparted by translating the master grating or the recording substrate between successive masked subgrating exposures.

1 Control of substrate optical thickness and thus phase shift φ_i : Figure 7 shows a two

2 segment grating wherein the subgratings are written onto a substrate of varying

3 thickness. Variation in substrate thickness provides for control over the subgrating

4 parameter φ_i. More generally, φ_i can be controlled by any of the means known in the

5 art for varying the optical path length of the subgrating substrates. For example, index

6 of refraction changes between subgrating substrates provides for control over φ_i.

7

8 A variety of fabrication methods support control over φ_i. Lithography provides for

9 changes in surface level (and hence substrate thickness) as well as groove profile.

10 Programmed lithographic variations in surface level thus provide control over φ_i.

11 Holographic, lithographic, or mechanical ruling methods can be implemented on a

12 substrate that has been prepared to have specified optical thickness throughout the

13 spatial region occupied by each subgrating. Control over optical thickness can be

14 achieved by any of the means known in the art including but not limited to etching and

15 thin-film coating.

16

17 The value of φ_i for each subgrating can also be controlled through use of a separate

18 phase mask placed over a constant thickness substrate.

19

20 Production of Segmented gratings through Fourier Synthesis: A grating may be

21 made by a Fourier synthesis method by superposition of multiple periodic gratings each

22 of which spans the entire width of the segmented grating. The constituent periodic

23 gratings have relative phases, amplitudes, and spatial periods such that when summed

24 they result in the segmented grating profile of interest. The constituent periodic gratings

1   are the Fourier components of the desired grating profile. The more Fourier

2   components used the more sharply defined the subgratings will be.

3

4   The gratings can be manufactured by holographic or lithographic methods. By exposing

5   a photosensitive substrate with multiple holographic exposures each of which writes a

6   particular constituent periodic grating, the desired grating profile can be recorded.

7   Lithographic means also provide for multipass writing wherein each pass is employed to

8   write one constituent periodic grating.

9

10   Gratings with specific groove profiles (Blazing): By using lithographic and holographic

11   methods the gratings may have an arbitrary modulation profile which include saw-tooth

12   blazed, square wave, sine wave, etc. in order to engineer the distribution of power into

13   the diffraction orders.   Figure 8 is a schematic of a grating similar to that shown in

14   Figure 2B, but with a saw-tooth modulation profile.

15

16   It is noted that the descriptions of the segmented gratings presented in this document

17   can be generalized to include gain gratings as well as absorption gratings, fiber gratings,

18   and gratings in frequency selective materials.

19

20   Dynamic Gratings: In the embodiments described above, the gratings have been static.

21   The following describes an embodiment wherein the gratings can be dynamically

22   reprogrammed with respect to their spectral filtering functions.

23

24   In the previously described embodiments, the spectral transfer function of the gratings

25   is determined by the parameters A_i , φ_i , x_i , and Λ_i of its constituent subgratings.

1 Generally speaking, any means known in the art that provides for dynamic control of

2 one or more of these parameters will enable dynamic reprogramming of gratings. A

3 variety of construction methods allow for dynamic reconfiguration of gratings. For

4 example: Control of φ_i and A_i through control of substrate or overlay index of refraction.

5 A grating created by the means described above may be overlain with a material whose

6 index of refraction can be controlled by any of the standard means known in the art

7 including, for example, applied electric field, pressure, current, or optical irradiation. If

8 the means of controlling the index of the overlayer is applied to act differentially over

9 spatial regions essentially coinciding with the subgratings comprising the grating either

10 φ_i or A_i can be controlled. To control φ_i alone, an overlayer may be applied to the side of

11 the substrate opposite to the grooves. Variation in optical thickness in the overlayer

12 induced by any means known in the art then allows one to vary φ_i. If the overlayer is

13 applied to the groove side of the grating (filling in the grooves) both φ_i and A_i can be

14 controlled. A_i may be controlled by changing the difference in refractive index between

15 the grooves and the overlayer. φ_i can be controlled by controlling the optical path length

16 of the overlayer (as in the case when the overlayer is applied on the substrate side

17 opposite the grooves). The ratio $\Delta A_i / \Delta \varphi_i$ may be varied by adjusting the thickness of

18 the overlayer. Here ΔA_i ($\Delta \varphi_i$) is the change in A_i (φ_i) introduced by a given change in

19 refractive index of the overlayer. Control of A_i alone can be achieved by a variety of

20 means including the addition of overlayers on both sides of the grating substrate and

21 configuration of the overlayers so that the optical path difference introduced by index

22 changes of the two layers cancels and thus so does the change in φ_i. On the other

23 hand, the change in amplitude of the phase subgratings is sensitive to the index change

1   of only one of the overlayers and does not cancel. Pure A_i control can also be obtained

2   by stacking two differentially controlled overlayers on the groove side of the grating.

3   Again, the optical path difference on passing through both layers is constrained to be

4   constant.

5

6   <u>Control of the complex φ_i through control of substrate or overlay transmission:</u>

7   In the following paragraph we reinterpret $h_i(x')$ in Eq. (1) to define the generalized

8   complex amplitude transmission function of a grating to be given by:

9   $$H_i(x')=\exp(jh_i(x'))\qquad\qquad\qquad(5)$$

10 In this representation we allow $h_i(x')$ to be complex in order to include gain or absorption

11 gratings in the above presented treatment. When the amplitude factor A_i is considered to

12 be complex, the imaginary part subsequently describes the loss or gain grating

13 amplitude. Furthermore, by generalizing φ_i to be a complex number, we include the

14 possibility of subgrating absorption or gain introduced by a variation in substrate

15 transmission or a superimposed amplitude mask.

16

17   A grating, as described earlier, may be overlain with a material whose optical intensity

18 transmission can be controlled by any of the standard means known in the art including,

19 for example, with a liquid crystal amplitude modulator or an electro-absorptive material.

20 If the means of controlling the transmission of the overlayer is applied to act differentially

21 over spatial regions essentially coinciding with the subgratings comprising the

22 segmented grating, the imaginary part of φ_i can be controlled. Changing φ_i will effect a

23 change in the transfer function $T(v)$ as described in Eqs. (1-4).

24

1   In the preferred embodiment shown in Figure 1, two optical channels are multiplexed

2   using OCDMA coding. As illustrated in the embodiment shown in Figure 9, additional

3   channels can be encoded, multiplexed, transmitted and then demultiplexed. In the

4   embodiment shown in Figure 9, four channels 901, 902, 903 and 904 are modulated by

5   modulators 901a to 904a, multiplexed by grating 919, transmitted on fiber 911,

6   demultiplexed by grating 919a, and then detected by detectors 901d to 904d. The

7   gratings 919 and 919a consist of four superimposed segmented gratings of the type

8   · previously described.

9

10   While the invention has been described with respect to preferred embodiments thereof,

11   it will be understood by those skilled in the art that various changes in format and detail

12   may be made without departing from the spirit and scope of the invention. Applicant's

13   invention is limited only by the appended claims.

14